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DEVELOPMENT OF A METHODOLOGY FOR THE QUANTIFICATION OF PARTICLE NUMBER AND GASEOUS CONCENTRATIONS IN A BI-DIRECTIONAL BUS TUNNEL AND THE DERIVATION OF EMISSION FACTORS

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Abstract

Particle number, NO_x and CO concentrations were measured simultaneously at the air entry portal and at the mid-point of a 511m bi-directional road tunnel, used entirely by urban public transport buses. The aim of this study was to provide information on concentrations of these pollutants inside a unique bus tunnel, and to develop a viable methodology for determining emission factors for on-road vehicles. Measurements were made continuously over a period of five days that included a complete weekend. Traffic flow rate and air flow rate were also monitored. The mean particle number concentration at mid-tunnel was 4.1 x 10^4 cm^{-3}, which was over four times higher than the urban background concentration. The mean concentrations of NO_x and CO at mid-tunnel were 464 ppb and 802 ppb, respectively. All these values were between 2 and 4 times higher than at the air entry portal. Median concentrations during selected time segments coinciding with the morning and evening rush hours, mid-day during weekdays and full day during the weekends were determined and the corresponding bus emission factors of each of the three parameters was calculated. Mean emission factors found for particle number, NO_x and CO were 7.1 x 10^{14} particles km^{-1}, 8.1 g

km^{-1} and 15.9 g km^{-1}, respectively. These values compared well with previous studies, showing that the methodology adopted was sound and viable.

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1. INTRODUCTION

Recent years have seen an increased demand for the planning and construction of road tunnels as a means of reducing traffic congestion in urban areas. This is expected to lead to an increase in exposure time and exposure levels to vehicle-induced pollutants inside these tunnels and has led to an increased effort to monitor pollutant levels. Furthermore, unlike on open roads, measurements within tunnels offer certain advantages for the determination of emission factors of vehicles such as the containment of vehicle emissions screened from the direct impact of outdoor weather conditions. In addition, if the tunnel is used by one type of vehicle, such as by a fleet of similar buses using the same type of fuel, it will eliminate other variables that may affect the estimation of emission factors.

El-Fadel et al. (2001) presented a critical review of measurement methodology of vehicular emission in roadway tunnels and concluded that modelling pollutant emissions and transport in and out of tunnels in general have been simplistic. Most research appears site specific and subject to variation in sampling, measurement procedures, instruments used, models applied and assumptions made, or implied by the model. The present study was designed to develop a methodology for the determination of pollutant concentrations in road tunnels, with a specific focus on establishing a method likely to provide accurate and consistent quantification of the dynamics of bus fleet emissions in a bidirectional bus-route urban tunnel. The dual aims of the investigation were to determine concentration levels of particle number,

NO_x and CO in the tunnel and to use these results to derive emission factors for the respective pollutants for a public transport bus fleet.

2. EXPERIMENTAL METHODS AND STUDY DESIGN

2.1 General overview

Particle number, NO_x and CO concentrations and other parameters, such as the air flow velocity and traffic flow rate, were monitored in a dedicated, bi-directional bus tunnel in an urban environment in Brisbane, Australia. Air sampling was carried out continuously over five consecutive days using two sets of harmonized instruments at the tunnel's air-stream entry portal and in mid-tunnel. The standard production equation was used to model the data and to estimate emission factors of the three parameters for buses.

2.2 Description of the tunnel

The measurements were conducted in a tunnel used exclusively by public transport bus fleets. The 511 m long single-tube tunnel has a cross-sectional area of approximately 60 m^2, with a single lane in each direction. The ventilation system is longitudinal, with three sets of axial fans mounted in the middle section of the tunnel, just below roof level. The following notation shall be used in the text: air intake portal (S_1); mid-tunnel (S_2) and the air exhaust portal (S3). The air stream in the tunnel was nominally unidirectional from S_1 to S_3.

2.3 Bus fleet and traffic flow

At the time of the study (2005), the fleet consisted of a wide mix of buses up to a maximum of 23 years in age. Approximately 34% of buses were fuelled with compressed natural gas (CNG) and the rest on ultralow sulphur diesel.

Traffic flow through the tunnel was monitored by four sensor-recorder systems; two in the lane inbound to the city (S_1 to S_3 in the tunnel) and two in the lane outbound from the city (S_3 to S_1 in the tunnel). The two sensors in each lane recorded the arrival and departure times of every bus. The system was also fitted with sensors to register the unique identity number of each bus.

2.4 Instrumentation and parameters measured

Particle number concentrations were measured with two TSI condensation particle counters (CPC's), model 3022, with a detection size range of 7 nm to 3 μm and an upper concentration level of 10^7 particles cm^{-3}. Data were logged at time intervals of 1s. CO and NO_x concentrations were monitored with TSI Q-Trak and ECOTECH ML9841 monitors, respectively, and logged at intervals of 60s and 5s respectively. A complete set of instruments were placed at each location S_1 and S_2. An ultrasonic air velocity monitor DURAG D-FL 200T was installed at S_2. Tunnel traffic volume data was obtained through the bus traffic control system.

All instruments were tested and calibrated in accordance to recommendations from the manufacturers prior to transfer to the measurement site. A set of measurements was carried out in the laboratory to determine particle losses in the sampling tubes. At the required flow speed, the sample loss in the tube was found to be less than 1%, and therefore considered negligible. Several subsidiary experiments were conducted in the laboratory using the above experimental arrangement to compare the readings of identical instrument pairs and, in the processing and analysis of the results, where applicable, the data acquired by the various pairs of instruments, at for example sites S_1 and S_2, were adjusted accordingly. Initial tests carried out at the tunnel portals showed that the particle concentration did not vary significantly across the cross section of the tunnel.

2.5 Sampling and data analysis

Measurements were carried out over a continuous period of five days with a full complement of instruments at each of sites S_1 and S_2. It was decided to separate the weekday data into three time segments according to the traffic flow rate as follows: morning peak (7-10 h) and afternoon peak (16-19 h) and mid-day (10-16 h). The extended period from 6 to 24 h was also analysed as another time segment. For the two weekend days (Saturday and Sunday), as there were no distinct peak traffic times, the full 24 h periods were used for the analysis. Emission factors (per km travelled) were calculated for every parameter, for each time segment, using the equation

$$EF = \frac{(C_2 - C_1)Av}{NL}$$

where

C_1 = concentration of the air pollutant of interest at entering the tunnel segment, i.e., at S_1

C_2 = concentration of the same pollutant at exiting the tunnel segment, i.e., at S_2

v = velocity of the air stream in the tunnel.

N = tunnel traffic flow rate during the measurement period.

L = the distance between the points of measurement, S_1 and S_2 (255 m)

A = cross-sectional area of the tunnel (60 m^2)

3. RESULTS

Figure 1(a) shows the traffic flow rate in both directions, averaged over 10 min intervals on Monday 20 June. The pattern was typical of a week day exhibiting morning and afternoon peak traffic periods, with a wide mid-day plateau of traffic flow. These are the three distinct time segments identified in section 2.5 - morning peak (7-10 h), afternoon peak (16-19 h) and mid-day plateau (10-16 h) as discernible in the figure.

Figure 1(b) shows the total particle number concentration measured by the CPC located at S_2 on Monday 20 June. The data clearly shows the bimodal distributions with peak concentrations during the morning and afternoon traffic periods. A similar, but less pronounced, bimodal distribution was observed at S_1. Figures 1 (c) and (d) show the concentrations of CO and NO_x, respectively, measured at S_2 on Monday 20 June. Both graphs show very pronounced bimodal distributions.

All pollutant concentrations were averaged over 10 min intervals. Table 1 gives the overall summary of the observations and results. Columns 1 and 2 show the selected time segments for the five days. C_1 and C_2 correspond to the concentrations at S_1 and S_2, respectively. The air velocity is positive from S_1 to S_2. The pollutant concentration values shown are the median values found in each of the eleven time segments. Median values were preferable over mean values due to the large and spurious concentration spikes observed at times when the exhaust plume of a bus passed across the sampling intake tube. From these data, emission factors were calculated for each parameter for each 10 min period and averaged over the duration of each time segment. The median emission factors of each parameter calculated for each time segment are also shown in Table 1. The mean values for the eleven segments are shown in the last row of the table.

4. DISCUSSION AND CONCLUSIONS

The measurements at S_2 provided important information on the pollutant concentrations in a road tunnel used exclusively by transport buses. The difference in concentrations between S_2 and S_1, due to the traffic in one-half of the length of the tunnel, afforded a means of estimating the emission factors of the respective pollutants. The diurnal pattern of the traffic flow rate provided a guide for a selection of time segments corresponding to peak and mid-day traffic.

The mean value of the particle number concentration at S_1 over the measurement period was 9.8 x 10^3 cm^{-3}, which is in good agreement with the typical urban background concentration values found around Brisbane (Meija et al., 2007). However, very often, especially during peak traffic times, the pollutant concentrations at S_1 were elevated above urban background levels due to the emissions from buses idling and accelerating from rest at the Mater Hill bus station just outside the entry portal.

The pollutant concentrations measured in the tunnel at S_2 were significantly higher than at S_1 in all time segments. For example, the average particle number concentration at S_2 was 4.1 x 10^4 cm^{-3}, which is over four times higher than the concentration at S_1 and the urban background concentration in Brisbane. These values may be compared with Gertler et al (2001) who found that the particle number concentration at the outlet of a tunnel used by both heavy and light duty traffic was about 10^5 cm^{-3} which was an order of magnitude greater than at the tunnel inlet.

In this study, the mean value of the particle number emission factor found was 7.1 x 10^{14} km^{-1}. Jamriska et al (2004) using two SMPS's set to sample particles in the size range 17 nm to 700 nm in the same tunnel, derived a mean bus emission factor of 3.11 x 10^{14} km^{-1}. Considering the respective particle size detection ranges, this is in good agreement with the present result. As there are no other studies reporting emission factors from buses in tunnel studies, we compare this value with results from other vehicular tunnels. Kirchstetter et al (1999) reported values of 4.1 x 10^{13} km^{-1} for light duty vehicles (LDV) and 2.5 x 10^{15} km^{-1} for heavy duty vehicles (HDV) in the Caldecott Tunnel, California. Kristenssen et al (2004) and Imhof et al (2006) determined values of 4.6 x 10^{14} and 1.4 x 10^{14} km^{-1} for mixed fleets in two Swedish tunnels. From these results, it appears that the bus emission factors lie between the values for LDV's and HDV's and are comparable to the average value for mixed fleets.

While noting that the fleet under investigation consisted of approximately 66% diesel and 34% CNG buses, it is instructive to compare the observed values with emission factors derived for diesel and CNG buses from this same fleet in dynamometer experiments. Ristovski et al (2006) tested twelve diesel buses from this fleet on a chassis dynamometer under steady state conditions and measured particle number emission concentrations with an SMPS and found emission factors ranging from 2.5 x 10^{14} particles km^{-1} at an engine load of 25% of maximum power to 6.7 x 10^{14} km^{-1} at full engine power. The present result of 7.1 x 10^{14} km^{-1} falls just above these values but is reasonable when taking into account the size detection range (10-400 nm) of the SMPS's used by Ristovski et al. compared to the CPC used here (7 nm to 3 μm). In another study, under similar conditions, Jayaratne et al (2008) measured the emission factors of thirteen CNG and four diesel powered buses from the same fleet using a TSI 3022 CPC to monitor the particle number concentration. For the diesel buses, they found emission factors ranging from 1.3 x 10^{14} km^{-1} at an engine load of 25% of maximum power to 1.8 x 10^{15} km^{-1} at full engine power. For the CNG buses, the corresponding values were 1.2 x 10^{13} km^{-1} and 6.5 x 10^{14} km^{-1}, respectively. Applying these results to the fleet using the tunnel, the calculated weighted averages for the fleet were 9.1 x 10^{13} km^{-1} and 1.4 x 10^{15} km^{-1} for engine loads of 25% and 100% power, respectively. The present experimental value derived using the identical CPC, 7.1 x 10^{14} km^{-1}, falls well within this range.

Although there are significant differences between these studies in terms of the instrumentation and their detection size ranges and taking into account that the fleet is a mix of two types of buses, the results are largely consistent, and it may be concluded that the method described here to determine emission factors of buses in the tunnel is robust and viable.

The mean concentrations of the two inorganic gases at S_2 (464 ppb and 802 ppb for NO_x and CO respectively) were between 2 and less than 4 times higher than at S_1. From these values, the mean value of the NO_x emission factor found was 8.1 g km^{-1}. Once again, this value lies between the values for HDV's (10-16 g km^{-1}) and LDV's (0.4-1.4 g km^{-1}) found in other tunnel studies (Pierson et al, 1996; Schmid et al, 2001; Kristenssen et al, 2004 and Imhof et al, 2006). The corresponding values found by Ristovski et al (2006) and Jayaratne et al (2008) for diesel buses ranged from 9.5 g km^{-1} and 6.9 g km^{-1}, respectively, at 25% load to 24.8 g km^{-1} and 19.0 g km^{-1},

Date	Time Segment	Traffic Flowrate	Air Velocity	Particle Number			NOx (ppb)			CO (ppb)		
	(h)	(bus h^{-1})	(m s^{-1})	(cm^{-3})	(cm^{-3})	(km^{-1})	(ppb)	(ppb)	(g km^{-1})	(ppb)	(ppb)	(g km^{-1})
				C2	C2-C1	EF	C2	C2-C1	EF	C2	C2-C1	EF
Thu16	16 to 19	109.7	1.85	5.09E+04	4.13E+04	5.91E+14	7.78E+02			1.17E+03	6.63E+02	11.8
Fri 17	7 to 10	122.3	2.46	5.28E+04	4.59E+04	7.84E+14	5.28E+02			6.93E+02		
	10 to 16	99.8	1.48	4.56E+04	3.63E+04	4.56E+14	9.43E+02			2.83E+02		
	16 to 19	99.3	1.15	5.41E+04	4.56E+04	4.50E+14	9.35E+02	9.20E+02	12.10	1.22E+03		
	6 to 24	83.0	1.69	4.56E+04	3.81E+04	6.56E+14	5.19E+02			7.97E+02		
Sat 18	0 to 24	41.3	2.13	3.25E+04	2.21E+04	8.25E+14	2.00E+02	1.66E+02	9.71	4.15E+02		
Sun 19	0 to 24	32.5	1.6	2.92E+04	2.37E+04	9.88E+14	1.50E+02	9.90E+01	5.53	4.21E+02		
Mon 20	7 to 10	114.0	4.23	4.03E+04	2.33E+04	7.31E+14	3.46E+02	1.94E+02	8.17	1.21E+03		
	10 to 16	101.0	4.1	3.09E+04	2.26E+04	8.00E+14	2.43E+02	1.84E+02	8.48	3.10E+02		
	16 to 19	107.7	3.83	3.81E+04	2.49E+04	7.50E+14	2.43E+02	1.13E+02	4.56	1.63E+03	5.32E+02	19.9
	6 to 24	85.2	4.11	3.10E+04	1.97E+04	8.03E+14	2.22E+02	1.52E+02	8.33	6.76E+02		
Mean and Std Dev				(4.1±0.9) E+04	(3.1±1.0) E+04	(7.1±1.6) E+14	(4.6±2.9) E+02	(2.6±2.9) E+02	(8.1±1.4)	(8.0±4.4) E+02	(6.0±0.9) E+02	(15.9±3.7)

Table 1: Overall summary of the observations and results. C_1 and C_2 are the pollutant concentrations at S_1 and S_2 respectively. EF is the emission factor. The missing data for CO and NO_x is a result of instrument failure at site S_1.

respectively, at 100% load. From these two studies, the mean values for diesel buses at the 25% and 100% loads are 8.2 and 21.9 g km^{-1} respectively. The corresponding. values found by Jayaratne et al (2008) for CNG buses ranged from 6.4 g km^{-1} at 25% load to 38.0 g km^{-1} at 100% load. This gives weighted fleet averages of 7.6 and 27.2 g km^{-1} at the 25% and 100% loads respectively. The present value of 8.1 g km^{-1} falls within this range and closer to the lower load, which is acceptable. For CO, in the present study, data were available for only two time segments. The average value was 15.9 g km^{-1}. This is considerably higher than the values found in tunnel studies for HDV of 5 g km^{-1} (Pierson et al, 1996 and Kristenssen et al, 2004), and also higher than in the dynamometer study by Ristovski et al (2006) for diesel buses – 1.6 g km^{-1} at 25% load to 6.9 g km^{-1} at full power. There are no dynamometer measurements of CO emission factors for CNG buses from this fleet. However, values from 9.5 g km^{-1} to 29.7 g km^{-1} have been reported for CNG operated school buses tested on transient cycles (Lanni et al, 2003; Ullman et al, 2003). Thus, we may conclude that the present results are in good agreement with previous dynamometer measurements.

The main difference between emission measurement studies in unidirectional and bidirectional tunnels is air turbulence. The movement of vehicles in one direction creates an additional airflow in the direction of motion. As observed during rush hour traffic, this flow can be quite significant when the traffic flow is high, especially when the traffic is moving in the direction of the enforced air flow by the ventilation fans.

When the traffic is moving in the direction opposite to the enforced air flow, there is considerable turbulence generated and the resultant air flow could be highly variable in both magnitude and direction. The effect is exacerbated in bidirectional tunnels, especially when the traffic flow in one direction is greater than in the other, such as during the rush hours.

The study provided valuable information of the pollutant concentrations in a bidirectional bus-route urban tunnel and compared the values with levels in the surrounding urban environment. The results confirmed that the method used to estimate emission factors of buses generated credible quanta for accurate and consistent quantification of the dynamics of bus fleet emissions in a tunnel environment.

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References

El-Fadel, M. and Hashisho, Z. 2001. Vehicular Emissions in Roadway Tunnels: A Critical Review. Critical Reviews in Science and Technology. 31(2),125-174.

Gertler, A.W., Abu-Allaban, M., Coulombe, W., Gillies, J.A., Pierson, W.R., Rogers, C.F., Sagebiel, J.C. and Tarnay, L. 2001. Measurements of mobile source particulate emissions in a highway tunnel. Int J Vehicle Design. 27, 86-93.

Imhof, D., Weingartner, E., Prevot, A., Ordonez, C., Kurtenbach, R. Wiesen, P., Rodler, J., Sturm, P., McCrae, I., Ekstrom, M. and Baltensperger, U. 2006. Aerosol and NO_x emission factors and submicron particle number size distributions in two road tunnels with different traffic regimes. Atmos. Chem. Phys. 6, 2215-2230.

Jamriska, M., Morawska, L., Thomas, S. and He, C. 2004. Diesel bus emissions measured in a tunnel study. Environ. Sci Technol. 38, 6701-6709.

Jayaratne, E.R., Ristovski, Z.D., Meyer, N. and Morawska, L. 2008. Particle and gaseous emissions from compressed natural gas and ultralow sulphur diesel fuelled buses at four steady engine loads. Submitted to Sci Total Environ.

Kirchstetter, T.W., Harley, R.A., Kreisberg, N.M., Stolzenburg, M.R. and Hering, S.V. 1999. On road measurement of the particle and nitrogen oxide emissions from light- and heavy-duty motor vehicles. Atmos. Environ. 33, 2955-2968.

Kristensson, A., Johansson, C., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U. and Vesely, V. 2004. Real-world traffic emission factors of gases and particles measured in a road tunnel in Stockholm, Sweden. Atmos. Environ. 38, 657-673.

Lanni, T., Frank, B.P., Tang, S., Rosenblatt, D. and Lowell, D. 2003. Performance and emissions evaluation of compressed natural gas and clean diesel buses at New York City's metropolitan transit authority. SAE Technical Paper Series, 2003-01-0300. Society of Automotive Engineers.

Pierson, W.R., Gertler, A.W., Robinson, N.F., Sagebiel, J.C., Zielinska, B., Bishop, G.A., Stedman, D.H., Zweidinger, R.B. and Ray, W.D. 1996. Real-world automotive emissions – summary of studies in the Fort McHenry and Tuscarora Mountain tunnels. Atmos. Environ. 30, 2233-2256.

Ristovski, Z.D., Jayaratne, E.R., Lim, M., Ayoko, G.A. and Morawska, L. Influence of diesel fuel sulphur on nanoparticle emissions from city buses. Environ. Sci. Technol. 2006, 40, 1314-1320.

Schmid, H., Pucher, E., Ellinger, R., Biebl, P. and Puxbaum, H. 2001. Decadal reductions of traffic emissions on a transit route in Austria – results of the Tauerntunnel experiment 1997. Atmos. Environ. 35, 3585-3593.

Ullman, T.L., Smith, L.R., Anthony, J.W., Slodowske, W.J., Trestrail, B., Cook, A.L., Bunn, W.B., Lapin, C.A., Wright, K.J. and Clark, C.R. 2003. Comparison of exhaust emissions, including toxic air contaminants, from school buses in compressed natural gas, low emitting diesel, and conventional diesel engine configurations. SAE Technical Paper Series, 2003-01-1381. Society of Automotive Engineers.

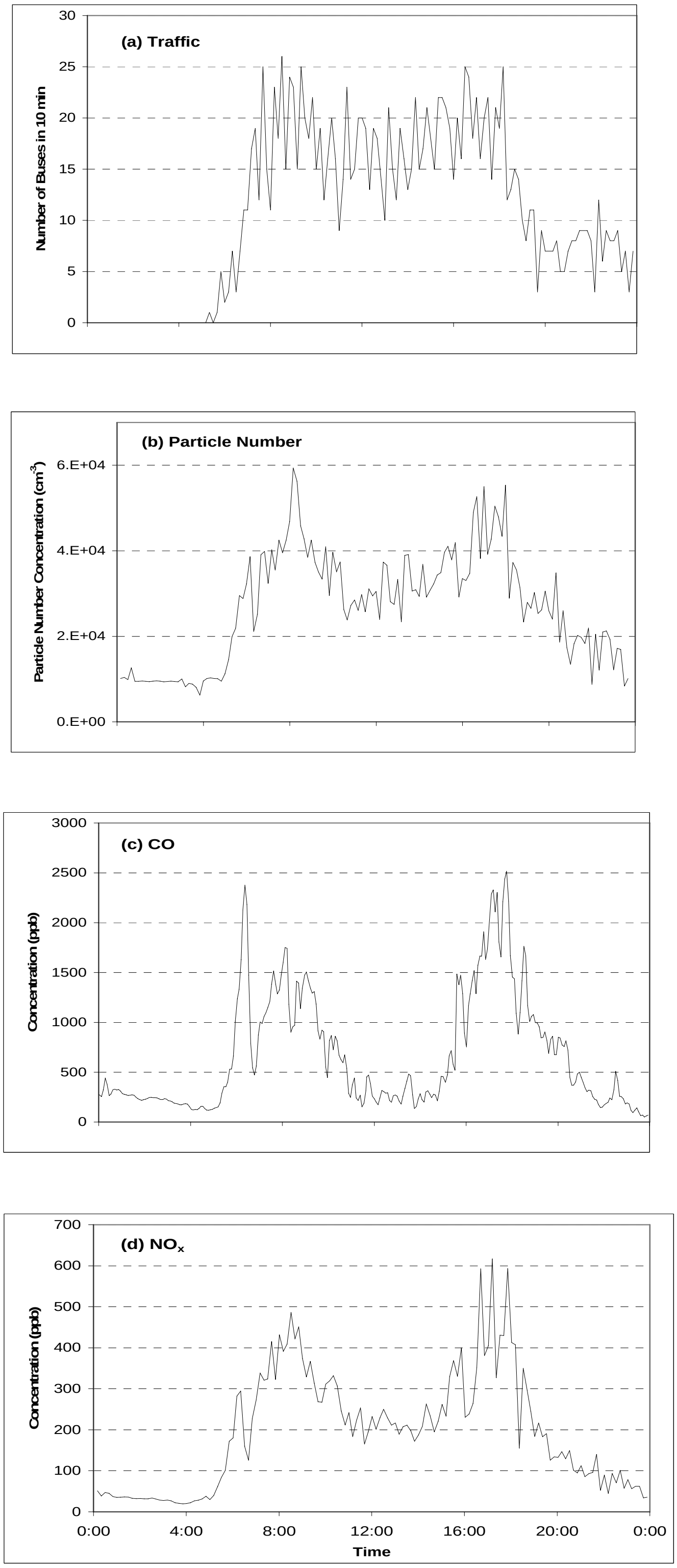

Fig 1: Measurements obtained on Monday 20 June: (a) traffic (b) particle number concentration (c) CO concentration and (d) NO_x concentration.